IMPACT OF INTERMITTENT POWER SUPPLY ON THE GERMAN POWER SYSTEM

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Abstract: *In Germany due to the continuous high expansion of the intermittent power supply capabilities of wind turbines and photovoltaic systems, the operational modes of thermal generation units will be influenced essentially until 2020 and beyond. The integration of this increasing share of intermitting generation while maintaining the present security level of supply confronts the existing power system with a big challenge. The fundamental problems are that the intermitting generation does not necessarily fit the power demand and is often located far away from the load centers. This results in physical limitations for integration of intermitting generation with regard to the existing infrastructure. Therefore it is has to be lined out that the acceleration time constant is reduced if some conventional power plant generators with masses are disconnected and replaced by the intermittent generators while the total nominal power value of the whole system remains constant. On the other hand more immediate acting acceleration power produced by the turbine-generator-systems of the conventional power plants will disappear because of shut down of these plants and related loss of inertia. With the reduction of inertia not only the frequency deviation after disturbances will increase substantially but also with more oscillation occurs and causes reduction of system stability. Therefore, different methods and tools to simulate the power plant scheduling will be presented and illustrated under different scenarios of Renewable Energy Sources (RES) to check whether the system is stable or unstable.*

Key words: *.wind, photovoltaic, inertia, oscillation, stability, primary control, Eigenvalues.*

1. Introduction

The potential of Renewable Energy Sources (RES) is enormous as they can in principle meet many times the world’s energy demand. Renewable energy sources such as biomass, wind, solar, hydropower, and geothermal can provide sustainable energy services, based on the use of routinely available, indigenous resources. A transition to renewable-based energy systems is looking increasingly likely as the costs of solar and wind power systems have dropped substantially in the past 30 years, and continue to decline, while the price of oil and gas continue to fluctuate [1 and 2].

In fact, fossil fuel and renewable energy prices, social and environmental costs are heading in opposite directions. Furthermore, the economic and policy mechanisms needed to support the widespread dissemination and sustainable markets for renewable energy systems have also rapidly evolved. It is becoming clear that future growth in the energy sector is primarily in the new regime of renewable, and to some extent natural gas-based systems, and not in conventional oil and coal sources. Financial markets are awakening to the future growth potential of renewable and other new energy technologies, and this is a likely harbinger of the economic reality of truly competitive renewable energy systems [3].

RES currently supply somewhere between 15% and 20% of world’s total energy demand. A number of scenario studies have investigated the potential contribution of renewable to global energy supplies, indicating that in the second half of the 21st century their contribution might range from the present figure of nearly 20% to more than 50% with the right policies in place. The situation in Europe differs from country to country. Circumstances may also differ between synchronous interconnected systems and island systems. The capacity targets and the future portfolio of RES depend on the national situation. Nevertheless, the biggest growth potential is for wind energy. The expectations of the European Wind Energy Association show an increase from 28.5 GW in 2003 to 180 GW in 2020 [4].

2. Development of Renewable Energy Sources in Germany

In Germany, the existing electrical generation system is going to be essentially influenced due to the continuously increasing influence of intermittent renewable energy sources. Because of the massive expansion of the total number of wind turbines, especially in the northern part of Germany within the last years, wind power (WP) now plays the most important role concerning the renewable energy sources in Germany [5].

Table 1 shows the installed capacity for renewable energy generation in Germany since 1990; at the end of 2012, the installed capacity of wind turbines amounted to more than 31.315 GW. Besides the photovoltaic (PV) capacities are increasing so fast, that at the end of 2012 there was more than 32.643 GW of installed capacity for photovoltaic systems. In the photovoltaic sector there was an increase of about 209 % compared to 2009 [6].

Despite of a stepwise reduction of the feed-in tariffs for the electrical energy produced by photovoltaic systems and wind turbines in Germany within the next 10 years, current predictions yield to about 50 GW of installed capacity for photovoltaic systems and an installed capacity of wind turbines of more than 51 GW in 2020. This means that there will be probably more than 100 GW of wind and solar power generation installed in Germany by the end of the decade. Therefore, the share of electrical energy produced by these two renewable sources could increase from 12.6% in 2012 to more than 35% in 2020 of the German electrical net energy consumption [7]. Fig. 1 shows the expected growth of installed capacities of wind turbines (on and offshore) and photovoltaic systems in Germany; at the end of 2020, the installed capacity of wind turbines and photovoltaic systems amounted to more than 51 GW and 51.7 GW respectively.

Table 1: Installed capacity for RES in Germany since 1990

	Hydropower MW	Wind Energy MW	Bio-mass MW	Photo-voltaic MW	Geo-thermal MW	Total Power GW
1990	3429	55	584	1	0	4.069
1991	3394	106	595	2	0	4.097
1992	355	174	604	3	0	4.331
1993	3509	326	643	5	0	4.483
1994	3563	618	677	6	0	4.864
1995	3595	1121	740	8	0	5.464
1996	3510	1549	804	11	0	5.874
1997	3525	2089	845	18	0	6.477
1998	3601	2877	972	23	0	7.473
1999	3523	4435	1022	32	0	9.012
2000	3538	6097	1164	76	0	10.875
2001	3538	8750	1282	186	0	13.756
2002	3785	11989	1417	296	0	17.487
2003	3934	14604	1884	435	0	20.857
2004	3819	16623	2527	1105	0.2	24.074
2005	4115	18390	3561	2056	0.2	28.122
2006	4083	20579	4322	2899	0.2	31.883
2007	4169	22194	4943	4170	3.2	35.479
2008	4138	23826	5510	6120	3.2	39.597
2009	4151	25703	6156	10566	7.5	46.584
2010	4395	27191	6594	17554	7.5	55.742
2011	4401	29071	7324	25039	7.5	65.843
2012	4400	31315	7647	32643	12.1	76017

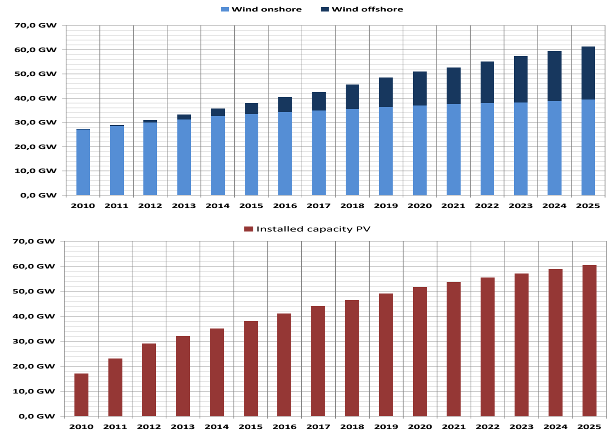

Fig. 1. Expected growth of installed capacities of WP and PV in Germany

3. Challenges on Power Balance and Frequency Control

Fig. 2 shows a simplified scheme of the power production /consumption structure within the model. The crucial item in this balancing equation is the residual load in each time step that has to be provided by the dispatchable power generation. At each time the residual load is calculated as the difference between the power of the consumers and the power produced by the non-dispatchable generation (WP, PV). Therefore as long as the non-dispatchable generation is smaller than the consumed power the residual load is positive. Today this is normally the case all the time because the installed capacities and therefore the maximum simultaneously produced power from these sources is smaller than the network load. The residual load is covered by the dispatchable generation where here the fossil and nuclear plants as well as the pumped storage power stations belong to. Hence the dispatchable generation is balancing the intermittent power generation in addition to the consumers demand characteristics.

In future, due to heavily increasing capacities, especially for the wind turbines and photovoltaic systems, the residual load will become negative values in several time periods over the year. In these cases more power is produced than consumed in a single country due to convenient weather conditions in this region. In these cases the power balance would only be observed if the dispatchable generation would become negative what respectively means that storage capacities will be in operation. But unfortunately the existing storage capacities won't fit the expected demand in the near future. Hence to observe the active power balance in the system occurring excess power produced by renewable sources has to be curtailed to keep the system stability in some periods in the future if no sufficient transmission line capacities are available to transport the power to other regions.

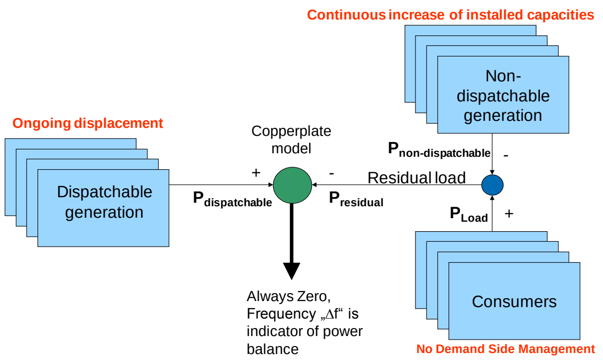

Fig. 2. A simplified scheme of the power balance of the generation system

4. Detailed Overview of the Power Balance of German Power System

A detailed non-linear dynamic model of the German power system was developed and Fig. 3 shows the overview of the power balance of German system with all power plants (nuclear power plants (NPP), old and new lignite power plants, old and new hard coal power plants, gas power plants (GPP), old and new combined cycle power plants (CCPP), hydropower Plants (HPP), combined heat and power (CHP)…etc.). The conventional power plants (e.g. thermal, gas, nuclear and hydropower plants…etc.) have different transfer functions between frequency and mechanical output power of the turbines. All power plants with their primary controllers and loads of German power system are modelled completely in detail. The resulting frequency deviation depends on the power difference, load-damping constant D and the inertia constant ($T_N=2*H_N$). Where H_N is the inertia constant of the system in seconds and T_N is the acceleration time constant of the total network in seconds.

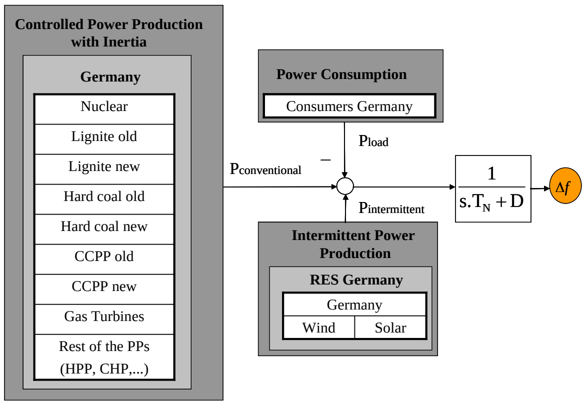

Fig. 3. Overview of the power balance of German power system

Any model consists of separate models for power controller, governor and turbine regulator as shown in Fig. 4. Where $P_{setpoint}$ is the power setpoint, Δf is the frequency deviation, Y_{tref} is the set point position governor guide vane, Y_t is the position governor guide vane and P_m is the mechanical power.

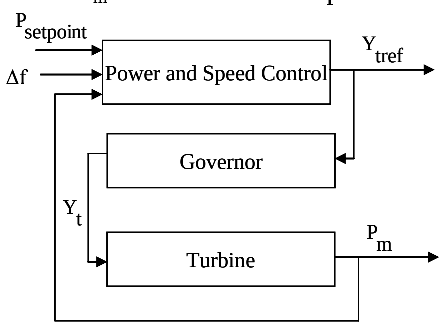

Fig. 4. General representation of sub-models

T_N is calculated by the inertia of the generators and motors, commonly states how much time it takes from standstill to accelerate an inertia that is driven by its nominal torque or power until the nominal rotational speed is reached. Within the electrical energy system the inertia is of vital importance, since only the inertia is able to stabilize the network frequency at an acceptable value in the first moment after a disturbance of the power balance. Normally wind turbines are connected to the system via frequency inverters and photovoltaic systems are always connected via DC/AC converters, so they are mechanically and electrically decoupled from the system and cannot increase the acceleration time constant. Therefore, it has to be lined out that the acceleration time constant is reduced, if more renewable energy sources (WP and PV) are connected to the system when at the same time the number of conventional power plant generators with masses are displaced by these intermittent generators as shown in the Fig. 5 while the total nominal power value of the whole system remains constant.

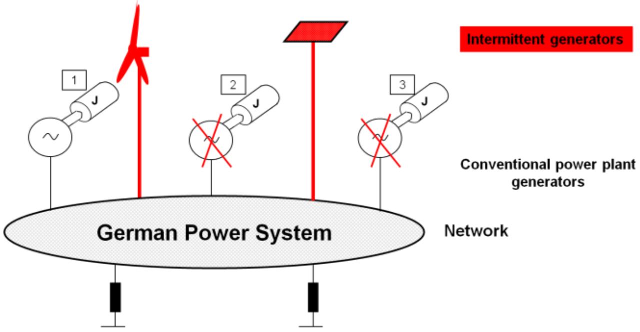

Fig. 5. German Power System

The acceleration time constant can be calculated by equation (1) [8].

$$T_N = \frac{\sum_{i=1}^{n} T_{G_i} . P_{G_i}}{\sum_{i=1}^{n} P_{G_i} + P_{RES}} \text{ and } T_{G_i} = \frac{J . \Omega_N^2}{P_{G_i}} \qquad (1)$$

Where T_{Gi} is the acceleration time constant for individual units in seconds, P_{Gi} is the rated power of an individual Generator in MW, P_{REF} is the intermittent rated power in MW, J is the moment of inertia of the rotor mass in kg-m^2 and Ω_N is the angular velocity of the mass J in radians per second.

From the moment that a load imbalance is produced in the network to the moment where the grid frequency is fully stabilized, several mechanisms take place in the power system during different stages (but in this paper we took only the first two stages), which depend on the duration of the dynamics involved as shown in Fig. 6. These stages are:

1. Distribution of power impact and inertial response.
2. Primary frequency control or governor response starts within seconds.
3. Secondary frequency control replaces primary control after minutes by the responsible partner.
4. Tertiary control frees secondary control by rescheduling generation by the responsible partner

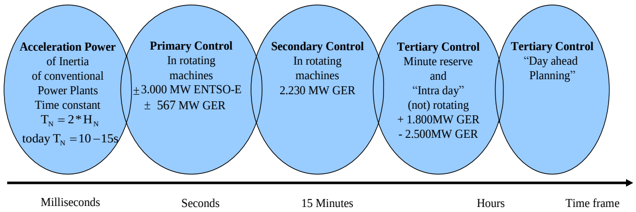

Fig. 6. Control scheme of electrical power systems

5. Analysis of Different Scenarios for German System

Fig. 7 shows the description of the different scenarios for the German system when increasing the intermittent renewable energy in operation (wind and photovoltaic) for the second and third scenarios to 50% and 81% respectively compared to the first scenario with no intermittent renewable energy in operation (0% wind and photovoltaic).

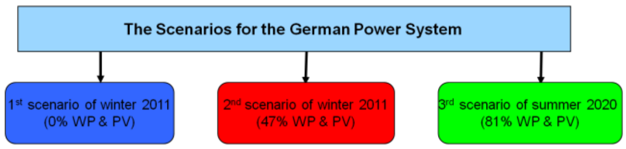

Fig. 7. The description of the different scenarios for the German power system

5.1 First Scenario of Winter 2011 (0% WP and PV)

Fig. 8 shows the first scenario of winter 2011 with no intermittent renewable energy in operation (0% wind and photovoltaic). The power plants in operation are hard coal power plants, lignite power plants, gas power plants (GPPs) and combined cycle gas power plants (CCGPPs). Power plants which are in operation but do not contribute to the primary control are hydropower plants (HPPs), combined heat and power plants (CHP) and nuclear power plants (NNPs).

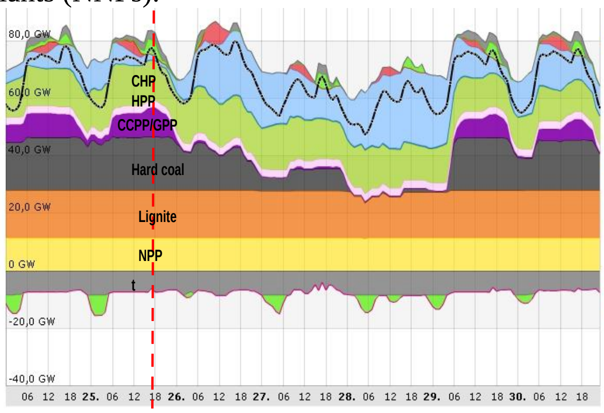

Fig. 8. First scenario of winter 2011

The total amount of the primary control reserve in German system is 700 MW. Fig. 9 shows that the contribution of the primary control reserve in the first scenario of winter 2011 is 25% allocated to hard coal power plants, 25% allocated to lignite power plants, 25% allocated to gas power plants and 25% allocated to combined cycle gas power plants.

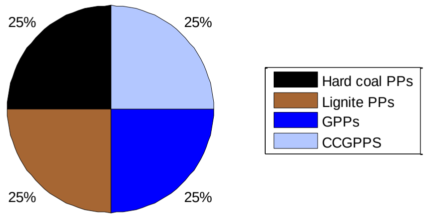

Fig. 9. Contribution of the primary control reserve in the first scenario

5.2 Second Scenario of Winter 2011 (50% WP and PV)

Fig. 10 shows the second scenario of winter 2011 with 50% intermittent renewable energy in operation (wind and photovoltaic). In this scenario, the gas power plants and some of the hard coal power plants are shut down and replaced by wind and photovoltaic power plants (50%). Power plants which are in operation but do not contribute to the primary control are hydropower plants, combined heat and power and nuclear power plants.

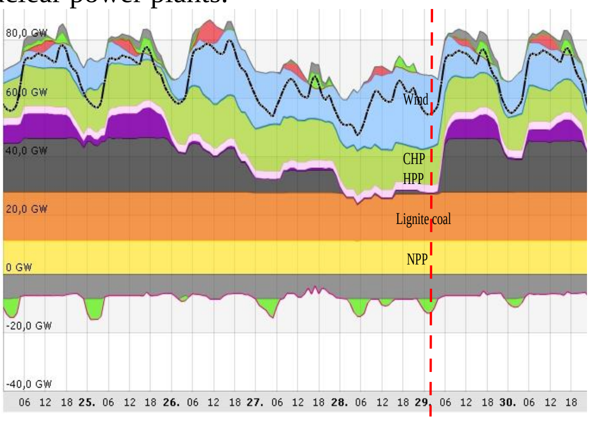

Fig. 10. Second scenario of winter 2011

Fig. 11 shows that, the contribution of the primary control reserve in the second scenario of winter 2011 is 31% allocated to hard coal power plants, 44% allocated to lignite power plants and 25% allocated to combined cycle gas power plants.

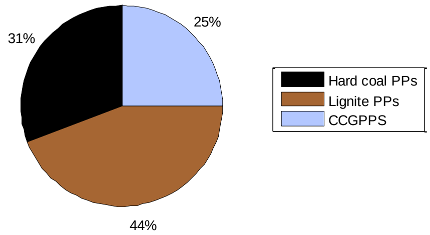

Fig. 11. Contribution of the primary control reserve in the second scenario

5.3 Third Scenario of Summer 2020 (81% WP and PV)

The Nuclear power plants phase-out planned until the end of 2020. Therefore, Fig. 12 shows the third scenario of summer 2020 with 81% intermittent renewable energy in operation (wind and photovoltaic). In this scenario the gas and nuclear power plants are shut down and replaced by wind and photovoltaic power plants (80%). Power plants which are in operation but do not contribute to the primary control are hydro power plants and combined heat and power plants.

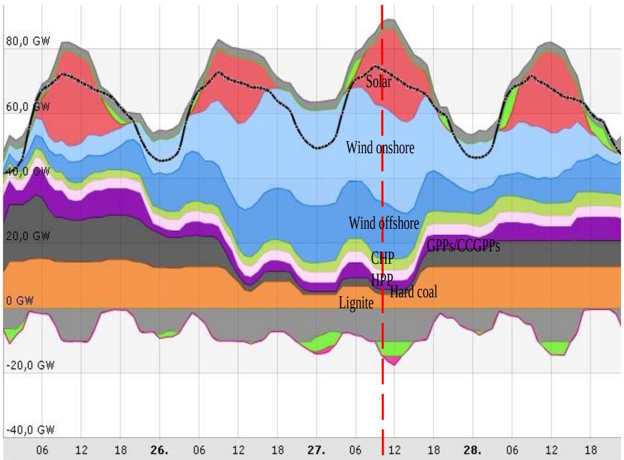

Fig. 12. Third scenario of summer 2020

Fig. 13 shows that, the contribution of the primary control reserve in the third scenario of summer 2020 is 45% allocated to hard coal power plants, 45% allocated to lignite power plants and 10 % allocated to combined cycle gas power plants.

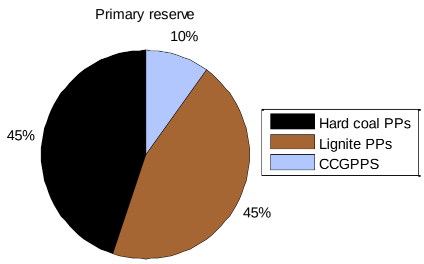

Fig. 13. Contribution of the primary control reserve in the third scenario

6. Simulation Results

The simulation results have been performed for three scenarios as explained before. After 5 seconds 700 MW generation loss in German power system, Fig. 14 shows the frequency response and turbine power for the first scenario (blue line), second scenario (red line) and the third scenario (green line). Due to switching off power plants and replacement by RES to increase to 50% and 81% in German system, the existing inertia mass in the grid decreases and deeper frequency deviation (nadir) with more oscillation occurs and shorter oscillation period. With shorter oscillation period, the phase shift between input frequency deviation and output power deviation produce greater delay as shown in Fig. 14 ($\varphi_3 < \varphi_2$). As results, for the first scenario with no intermittent renewable energy in operation, T_N is calculated to 9.9s and the frequency deviation will reach -290 mHz. For the second scenario, the intermittent renewable energy is increased to 50%, the existing inertia mass in the grid will decrease, T_N is decreased to 5s and the frequency deviation will reach -550 mHz with some oscillation occurs. For the third scenario, the intermittent renewable energy is increased to 81%, the existing inertia mass in the grid is decreased more and T_N is decreased to 2s and the frequency deviation is decreased to less than -800 mHz with more oscillation occurs. Therefore, some protection devices will operate and switch off some consumers/customers.

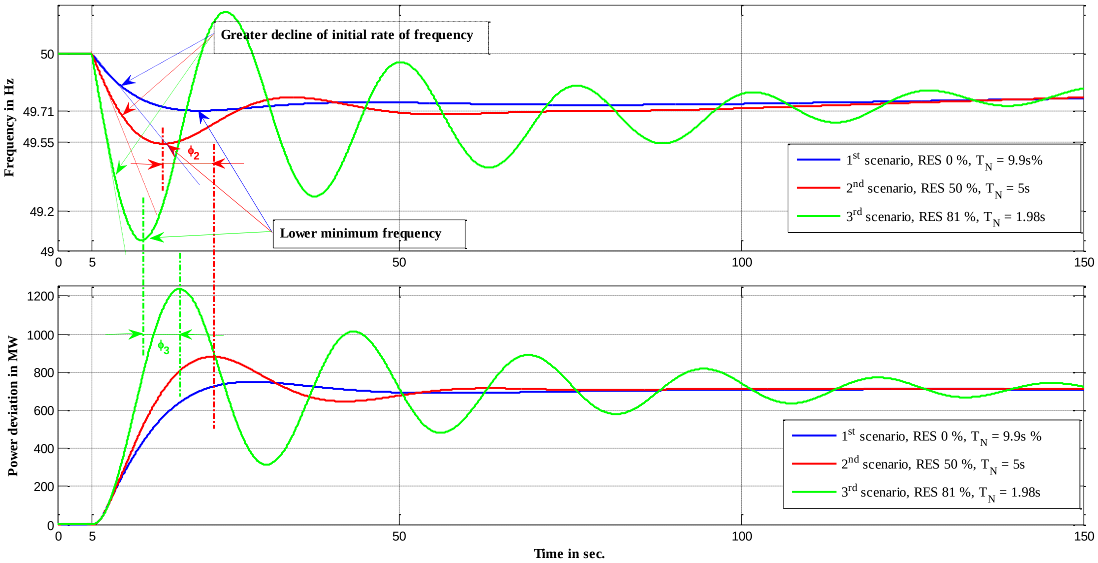

Fig. 14.Comparison of all scenarios for frequency and turbine power deviation

Finally, we can conclude that further increase of renewable energy sources in the grid will result in a reduction of the number of connected conventional power plants and this will lead to a reduction of inertia in the grid. This will show a greater decline of the initial rate of frequency. Lower system inertia will result in larger and faster frequency deviations after occurrence of abrupt variations in generation and load.

7. Computation of Eigenvalues for German Power System

The computations of the eigenvalues have been performed for the German model to make sure that the results from the simulation model are similar. Fig. 15 shows the computation of the eigenvalues of German model for scenarios 1, 2 and 3, as well as the most associated state variables to each eigenvalue, the undamped natural angular frequency ω (or eigenfrequency) and the damping ratio ζ. Let $\alpha \pm j\beta$ be a pair of complex conjugate eigenvalues, the eigenfrequency is defined as $\omega = \sqrt{\alpha^2+\beta^2}$ while the damping is $\zeta = -\alpha/\sqrt{\alpha^2+\beta^2}$. The damping is positive if the mode is stable (i.e. $\alpha < 0$). The natural frequency is how fast the motion oscillates and the damping ratio is how much amplitude decays per oscillation [9].

As a result, when increasing the RES, the system inertia decreases, lead to the eigenfrequency increases and the damping decreases for scenarios 2 and 3 compared to scenario 1. The eigenvalues of second and third scenarios approaches more to unstable region and then the system will oscillate faster.

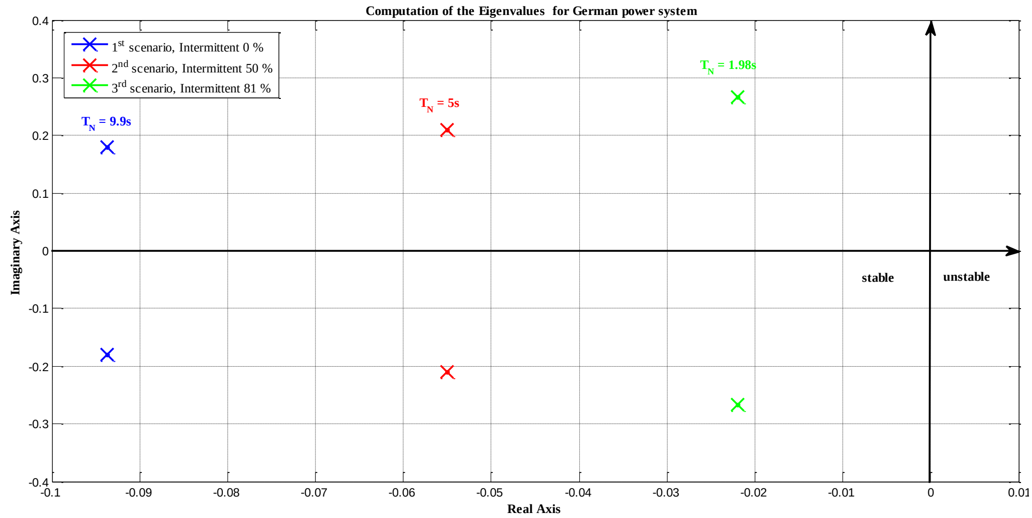

Fig. 15.Computation of eigenvalues for scenarios 1, 2 and 3 for the German Model

8. Conclusion

The methods and tools to simulate the power plant scheduling were presented and illustrated by different scenarios of intermittent generation. With the reduction of the number of conventional power plants during particular time periods the inertia time constant of the system will also be reduced. With this reduction not only the frequency deviation after disturbances will increase substantially but also the oscillation frequency of the so called “Primary Control Oscillation”. So with a fraction of 81% renewable in Germany the deviation after a 700 MW-disturbance will be increased from 390 to 900 mHz, while the oscillation frequency will change from 24 to 43 mHz. In this situation the power system is influenced seriously, because consumers and coupling lines can be tripped simultaneously which can result in islanding of the system. But also the higher rate of primary control oscillation frequency will reduce life time of the involved power plants. Finally, we conclude that a sufficient capacity from conventional generation has to be in the system at any time to keep it stable.

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